



**AFRL-AFOSR-CL-TR-2015-0003**

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Content dynamics over the network cloud

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**Abstract**

The project was concerned with dynamics in telecommunication networks, with principal focus on peer-to-peer dissemination systems. The main contributions are advanced mathematical models for content propagation and exchange mechanisms, based on tools from queueing theory, dynamical systems and control, applied to explaining the observed behavior in practically deployed systems, as well as indicating methods for improving performance.

A first line of work was to develop the theory for a fluid-PDE model for content evolution in peer-to-peer networks, initiated in our previous AFOSR/SOARD project. In this line we have the following contributions: We established the foundation for our models by rigorously proving their mathematical relationship with queueing systems [1,11]. We included heterogeneity in the model for peer access bandwidth, analyzing its impact on dynamics [5]. The control-theoretic analysis of our fluid-PDE dynamics, as well as empirical validations, were covered extensively in the journal article [12]; some additional results on global stability were obtained in [8].

A second line of contributions referred to the relationship between the microscopic mechanisms for piece exchange in peer-to-peer, and the resulting bandwidth allocation. In particular we studied a proportional reciprocity mechanism [4, 9] which idealizes some of the desirable features of the problem, and allows for a mathematical prediction of performance. We further studied in those references and the thesis [7] how to approximately implement this allocation through neighbor selection, for which we invoked stochastic optimization techniques such as the Gibbs sampler.

A third line concerns situations in which the spatial topology of the network has an impact on file-sharing. In particular we were interested in wireless ad-hoc networks, where P2P offers a simple dissemination solution but must address the fact that communication bandwidths are influenced by location. Optimal sharing schemes tailored to this setting were analyzed in [10] and the thesis [7], and a journal version is in preparation.

Additionally, during this project we also completed the publications [2, 3, 6] stemming from our previous project on cross-layer network optimization.

## Accomplishments/New Findings

We report separately on the areas of research indicated in the abstract.

### 1. Fluid models for population and content dissemination in peer-to-peer networks.

We work here with fluid models of a P2P swarm, which track populations of peers as a function of their download progress expressed by residual work. In prior work we introduced such models and validated their relevance to practical P2P systems.

- The relationship between our fluid-PDE models and stochastic queues was studied in [1] and further developed in our journal article [11]. For a peer-to-peer swarm with homogeneous network access parameters, we have established that the resulting file-sharing closely matches a Processor Sharing discipline, in which all downloading peers equally share available upload resources. In the P2P case under fixed servers (seeders) this yields to a combination of the  $M/G/1$ -PS and  $M/G/\infty$  queues; using recent results on insensitivity of the stationary distributions of such queues, it is possible to carry out a scaling limit, from which a fluid stationary model emerges, consistent with the steady-state of our fluid-PDE model. Fluctuations around this mean can further be characterized by a functional Gaussian approximation. In the case where the seeder population is slowly time-varying, a further analysis through separation of time-scales provides a characterization of the steady-state limit and its fluctuations. Results were validated against packet-level simulations.
- The aforementioned models of population dynamics in peer-to-peer file sharing systems apply to a single class of peers with homogeneous network access parameters. When upload bandwidths are heterogeneous, reciprocity mechanisms lead to non-uniform download rates and a more complex multi-class dynamics. We first addressed this situation in [5], both for ordinary differential equation models, and for the more detailed PDE case. The strongest results apply to a proportional reciprocity model in which mutual download bandwidths are allocated in proportion to the upload speed, plus a uniformly distributed server component. Partial results can also be given for a system where a fraction of mutual bandwidth is uniformly allocated, which represents some features of current protocols.
- From a dynamics and control perspective, the PDE dynamics is a challenging object because of its infinite dimensionality and nonlinearity. It was shown in [12] how different tools from control theory (Lyapunov, small-gain, frequency domain) apply to establishing local stability and noise response of the resulting equilibrium profile. What is even more challenging is to provide global stability: in [8] we showed how such results follow from the theory of monotone dynamical systems.

### 2. Analysis of reciprocity mechanisms in peer-to-peer

The preceding contributions look at the population dynamics from a macroscopic point of view, with an idealized model of bandwidth allocation among peers. In practice such allocation is determined by the microscopic piece exchange rules, most importantly the reciprocity mechanisms imposed by protocols to guarantee peer participation and avoid free riding. Is it possible to analyze such reciprocity schemes from a mathematical point of view? While some of

the prevailing schemes are of heuristic type and difficult to model, it turns out that there is a natural proportional reciprocity method that is both recommendable to provide transparent incentives, and amenable to mathematical modeling.

- From a mathematical perspective, proportional reciprocity can be characterized in terms of a suitable convex optimization problem in matrix space (the matrices of mutual exchange bandwidths) and furthermore a decentralized algorithm inspired in matrix renormalization can be used to achieve this allocation. These studies are given in [4, 9].
- From a practical perspective, the preceding algorithm is not suitable since it requires a fine control of transmission rates among peers. We further studied in [4, 9] and the thesis [7] whether this control could be replaced by an adequate neighbor selection. Techniques from Gibbs sampling based on a suitable energy function were employed to derive such algorithm, which compares favorably with alternatives in simulation studies.

### **3. Peer-to-peer dissemination in wireless networks.**

The preceding work describes peer-to-peer networks in the most common setting, that of a wired network subject to an upload bandwidth constraint. Given the success of this dissemination strategy, it is natural to consider its potential in other less-structured scenarios, in particular wireless ad-hoc networks in which a set of agents distributed in a certain area cooperatively engage in dissemination of files of common interest. The wireless substrate poses at least two additional challenges.

- In contrast to the wired case, variations in quality of mutual wireless channels imply that not all peering choices have equal bandwidth. This means there is a tradeoff between an efficient use of the medium and achieving the desirable reciprocity in the exchange. This tradeoff, and decentralized means to achieve it, were analyzed in [10].
- A second difficulty arises due to interference between wireless channels. This imposes an additional question of scheduling to the preceding tradeoff. An initial exploration of schemes to negotiate this tradeoff was pursued in the thesis [7], based on the Gibbs sampler. An extension of the work in [10] based on optimization to this setting is under preparation for a journal publication.

## Publications

(available from <http://fi.ort.edu.uy/innovaportal/v/2243/5/fi.ort.front/publications.html>)

1. A. Ferragut, F. Paganini, "Content Dynamics in P2P Networks from Queueing and Fluid Perspectives", *International Teletraffic Congress*, Krakow, Poland, Sept 2012, pp. 145- 152.
2. M. Zubeldía, A. Ferragut, F. Paganini, "Averting Speed Inefficiency in Rate-Diverse WiFi Networks through Queueing and Aggregation", in *Proc. IEEE Globecom*, Anaheim, CA, Dec 2012, pp. 5446-5452.
3. M. Zubeldía, A. Ferragut, F. Paganini, "Overcoming Performance Pitfalls in Rate-Diverse High Speed WLANs", *Computer Networks* 57(2013), 3673-3685.
4. M. Zubeldía, A. Ferragut, F. Paganini, "Proportional fairness in heterogeneous peer-to-peer networks through reciprocity and Gibbs sampling" *Proc. Allerton Conference*, Monticello, IL, pp. 123-130, Oct 2013.
5. F. Paganini, A. Ferragut, M. Zubeldía, "Dynamics of heterogeneous peer-to-peer networks", *Proc. IEEE Conference on Decision and Control*, Firenze, Italy, Dec 2013, pp. 3293-3298.
6. A. Ferragut, F. Paganini, "Network resource allocation for users with multiple connections: fairness and stability", *IEEE/ACM Trans. on Networking*, Vol 22, No 2., pp. 349-362, Apr 2014.
7. M. Zubeldía, "From resource allocation to neighbor selection in peer-to-peer networks", MS Thesis, Universidad ORT Uruguay, 2014. <https://bibliotecas.ort.edu.uy/bibid/79188/file/1223>
8. F. Paganini, A. Ferragut, "Monotonicity and global stability in download dynamics of content-sharing networks", *Proc. IEEE Conference on Decision and Control*, Los Angeles, CA, Dec 2014, pp. 5314-5317.
9. M. Zubeldía, A. Ferragut, F. Paganini, "Neighbor selection for proportional fairness in P2P networks", *Computer Networks* 83 (2015), 249-264.
10. F. Paganini, M. Zubeldía, A. Ferragut, "Trading Off Efficiency and Reciprocity in Wireless Peer-To-Peer File Sharing", *WiOpt* 2015, Mumbai, India, May 2015.
11. A. Ferragut, F. Paganini, "Queueing analysis of peer-to-peer swarms: stationary distributions and their scaling limits", *Performance Evaluation* (2015). In press, available online at <http://dx.doi.org/10.1016/j.peva.2015.08.003>
12. A. Ferragut, F. Paganini, "Fluid models of population and download progress in P2P networks", *IEEE Trans. on Control of Network Systems*. In press, available online at <http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7109155>.

## Personnel Supported by this Grant at Universidad ORT Uruguay

Fernando Paganini.	PI, Professor of Engineering
Andrés Ferragut	Co-PI, Associate Professor
Martín Zubeldía	Graduate student.

## Interactions/Transitions

- a) Presentation of paper [1] by A. Ferragut at ITC 24, Krakow, Poland, September 2012.
- b) Presentation by the PI “Content propagation and reciprocity in p2p file exchange networks”, AFOSR Complex Networks Program Review, Washington, DC, Dec 2012.
- c) Presentation of paper [2] by M. Zubeldía at IEEE Globecom, Anaheim, CA, Dec 2012.
- d) Invited seminar by the PI, “Dynamics of content propagation and reciprocity in p2p file sharing” at RSRG Seminar, Caltech, Pasadena, CA, Feb 2013.
- e) Invited seminar by the PI, “Dynamics of content propagation and reciprocity in p2p file sharing” at EE Seminar, Stanford University, CA, Feb 2013.
- f) Invited seminar by the PI, “Dynamics of content propagation and reciprocity in p2p file sharing” at UCLA-Electrical Engineering, Los Angeles, CA, Feb 2013.
- g) Invited seminar by the PI, “Heterogeneity and content dynamics in peer-to-peer file sharing” at University of Illinois, Urbana-Champaign, Sept. 2013.
- h) Presentation of paper [4] by M. Zubeldía at Allerton Conference, Monticello, IL, Oct 2013.
- i) Invited seminar by the PI “Mathematical modeling of traffic in data networks: between queues and fluids”, Center for Mathematics, Universidad de la República, Montevideo, Uruguay, Oct 2013.
- j) Presentation of paper [5] by the PI at IEEE CDC, Florence, Italy, Dec. 2013.
- k) Invited seminar by the PI “Population and download dynamics in peer-to-peer file sharing with heterogeneity”, Cornell University, March 2014.
- l) Invited presentation by A. Ferragut, “Processor sharing queues motivated by P2P networks”, Stochastic Networks Conference, Amsterdam, the Netherlands, June 2014.
- m) Invited seminar by the PI, “Controlling the Internet in the era of Software – Defined and Virtualized Networks”, Caltech CDS20 Workshop, Aug. 2014.
- n) Presentation by the PI “Content dynamics over the network cloud”, AFOSR Complex Networks Program Review, Arlington, VA, Nov 2014.
- o) Presentation of paper [8] by the PI at IEEE CDC, Los Angeles, CA, Dec. 2014.
- p) Invited seminar by A. Ferragut, “Dynamical models for P2P and power systems inspired by queueing theory”, RSRG Seminar, Caltech, March 2015.
- q) Presentation of paper [10] by the PI at WiOpt, Mumbai, India, May 2015.

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### **Archival Publications (published) during reporting period:**

1. A. Ferragut, F. Paganini, "Content Dynamics in P2P Networks from Queueing and Fluid Perspectives", International Teletraffic Congress, Krakow, Poland, Sept 2012, pp. 145- 152.
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